AD-A251 274

DTIC
ELECTE
MAY 2 9 1992
S C D

(2)

AD

TECHNICAL REPORT ARCCB-TR-92016

ANALYSIS OF THE SWAGE AUTOFRETTAGE PROCESS

G. PETER O'HARA

APRIL 1992

US ARMY ARMAMENT RESEARCH,
DEVELOPMENT AND ENGINEERING CENTER
CLOSE COMBAT ARMAMENTS CENTER
BENÉT LABORATORIES
WATERVLIET, N.Y. 12189-4050

92-14152

92 5 ... 100

DISCLAIMER

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

The use of trade name(s) and/or manufacturer(s) does not constitute an official indorsement or approval.

DESTRUCTION NOTICE

For classified documents, follow the procedures in DoD 5200.22-M, Industrial Security Manual, Section II-19 or DoD 5200.1-R, Information Security Program Regulation, Chapter IX.

For unclassified, limited documents, destroy by any method that will prevent disclosure of contents or reconstruction of the document.

For unclassified, unlimited documents, destroy when the report is no longer needed. Do not return it to the originator.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
April 1992

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
ANALYSIS OF THE SWAGE AUTOFRETTAGE PROCESS

5. FUNDING NUMBERS
AMCMS: 6111.02.H610.011
PRON: 1A04Z0CANMSC

6. AUTHOR(S)
G. Peter O'Hara

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Benet Laboratories, SMCAR-CCB-TL
Watervliet, NY 12189-4050

8. PERFORMING ORGANIZATION REPORT NUMBER
ARCCB-TR-92016

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Close Combat Armaments Center
Picatinny Arsenal, NJ 07806-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Presented at the ASME Pressure Vessel and Piping Conference, 28-29 June 1991, San Diego, CA.
Published in Proceedings of the Conference.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
The autofrettage process is a well-known method to improve the working strength and fatigue life of thick-walled cylinders. In the conventional viewpoint, the cylinder is pressurized beyond its elastic limit in order to produce a beneficial residual stress pattern with large compressive hoop stresses at the bore. In practice, this has been accomplished by the swage process in which an oversized tungsten carbide mandrel is pressed through the bore to produce a similar effect. The analysis of this problem has not been possible until the development of high-level finite element codes and high-performance vectorized computers. This combination was utilized to accomplish a detailed analysis of the swage process in a short section of a 105-mm cannon tube.

14. SUBJECT TERMS
Residual Stress, Autofrettage, High Pressure, Swage, Thick Wall

15. NUMBER OF PAGES
16

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

ACKNOWLEDGMENTS

The author wishes to thank Mr. G. Pflegl and Mr. R. Farrara for their aid and encouragement in this work.

NOMENCLATURE

a = Inner radius of a thick-walled cylinder

b = Outer radius of a thick-walled cylinder

R = The distance from a singular point

W = Wall ratio = b/a

ρ = The radius of the elastic-plastic interface

INTRODUCTION

The autofrettage process has been known for many years and has been used as an example of an elastic-plastic problem in countless books and college lectures in plasticity. In the conventional picture a thick-walled cylinder of inner radius a and outer radius b is assumed to have elastic-perfectly plastic material properties. Internal pressure is applied until the elastic-plastic interface is at some radius ρ. The problem is viewed from a cross section with either plane-strain or, more commonly, plane-stress end conditions. In this solution the cylinder geometry can be reduced to the single nondimensional parameter wall ratio $W = a/b$. The position of the elastic-plastic interface is often described in terms of the percent overstrain or the position of the interface as a percent of the wall thickness. Weigle (1,2) combined these assumptions with Mises' yield criterion on the basic theory. Davidson et al. (3) further expanded this work as a basis to analyze this problem.

The simple facts are that in manufacturing practice the use of high pressures to carry out the autofrettage process is complex, slow, expensive, and dangerous. This is because the maximum pressures are in the range of 1000 to 2000 MPa, and at the autofrettage pressure, the cylinders are close to failure. The swage process was developed by Davidson et al. (4) as a way to overcome these problems and has been in use for over 25 years. The basic geometry is shown in longitudinal section in Figure 1. Here a solid tungsten carbide mandrel is forced through a carefully prepared tube using a solid steel ram. The interference between the mandrel and the tube is generally about 2.5 percent and produces residual stresses nearly the same as the calculated values. This problem does not yield to the classic theory of elasticity methods because of its complex nature as a three-body problem with two separate contact surfaces. This condition is further complicated by the fact that one of the contact surfaces moves along the length of the tube experiencing different conditions at the start and at the end of the ram stroke.

The advanced nonlinear finite element codes, such as ABAQUS (ref 5), are well-suited to this type of problem. In this type of analysis the global equations of elasticity are replaced by local element shape functions, and the nonlinear effects are handled by solving the problem in many small linear increments on high-performance computers. Under these conditions, the solution seems to improve as many small practical details are added and as the analysis more closely mirrors the actual geometry, material, constraint, and loading conditions. In this study there are two primary simplifying assumptions: first is that the behavior is symmetric about the tube center line (axisymmetric elements), and second is that the material properties can be represented by a bilinear stress-strain curve with kinematic strain-hardening.

The full swage autofrettage process had been well-defined and was being used as a routine production process for several years before the analytical tools became available for the problem. The first key tool was the ABAQUS code which was quickly demonstrated to be a reliable and powerful nonlinear finite element code. Next, there was a need for a computer with sufficient power to solve a reasonable size mesh. The installation of a CONVEX C-220 completed the required 'tool kit' for the swage problem. The final motivation was the necessity to test the CONVEX computer with a problem having a long solution time. This preliminary solution of the full swage autofrettage problem required over 15 hours of computer time to complete. The time was well worth the effort as a computer system test and it yielded interesting technical results as well.

ANALYSIS DETAILS

The following is essentially a list of the analysis details necessary to closely model the swage process for a section of a 105-mm cannon tube that had a length of four bore diameters (0.405 m) and was modeled as a steel with a yield strength of 1195 MPa. The analysis starts with the mandrel being placed in the bore of the tube at the end nearest the axial restraint and it ends when the mandrel has cleared the tube and the tube is in the fully-developed residual stress condition. It is this residual stress condition that is the primary result of the analysis and will be plotted from a single section at midpoint in tube length. While the details of the process are fascinating in themselves, they are not the object of the current study.

The first body in the analysis chain is the solid steel ram which is used to push the mandrel through the tube. Here the ram is truncated to a length one-half the ram diameter and is moved through the tube by a moving constraint at the free end. This is the only applied load and its actual value is determined by the friction and wedging action between the tube and mandrel. This component interacts with the mandrel at a simple interface with a coefficient of friction of 0.05. The exact value of friction probably has little effect because of the low relative sliding on this interface. The interaction at the ram-mandrel interface was previously studied in a design analysis of swage mandrels (refs 6,7).

The mandrel is essentially a short tungsten carbide cylinder with a 1.5-degree taper over most of its length. There is a short (0.0063 m) constant diameter flat near the rear (ram) end followed by a 3-degree relief taper at the back. This component interacts with both the ram and the tube and has an interesting feature at the end of the ram travel. The analysis is interrupted about 0.075 m from the end of the ram stroke to add a second moving constraint at the front of the mandrel. This constraint controls the forceful ejection of the mandrel from the tube, as a result of the interaction with the 3-degree rear taper. This procedure keeps the analysis a static solution and eliminates the need for inertial terms.

The interface between the mandrel and the tube is a critical portion of the model because it is the location of the moving contact surface. Here the interface is modeled as a 'softened contact'. In this model the interface pressure becomes an exponential function of the gap between the two bodies. Contact starts at a numerical gap of 2.7×10^{-6} and reaches a value of 17.2 MPa at zero gap. This process makes the numeric solution more stable and may mimic the normal compliance of real surfaces. A coefficient of friction of 0.015 was used to model this surface which was lubricated by a sterate-based high pressure lubricant held in place by a porous phosphate coating.

The tube section used was a plane cylinder with a wall ratio W = 2.257 and modeled the rear portion of a 105-mm cannon tube. The tube material was a steel with a yield strength of 1195 MPa which strain-hardened to 1332 MPa at a plastic strain of 0.0368. The cylinder had three geometry details which were reflected in actual practice. First, it was restrained at a single point on the outer diameter (OD) to prevent axial movement. Actual tubes are held by a single groove in the OD. Second, the bore had a short (1.5-degree) taper to help the initial placement of the mandrel (also true in shop practice). Third, a small relief was placed on the exit end of the tube to ease the mandrel out of the cylinder. This took the form of a 0.00066-m increase in bore radius over the last 0.013 m of length.

The model was generated for the ABAQUS code using eight-node axisymmetric elements (CAX8). The geometry of the elements was modified at the point of axial restraint to properly model the 1/R singular stress field generated by this point load. The contact surfaces were both modeled as slide lines with the appropriate friction. The slide line on the bore covered all 64 elements on the bore. These 64 bore elements were reduced to 32 at the OD of the cylinder, resulting in 306 elements for the cylinder model, 56 elements for the mandrel, and 16 for the ram. The solution was quasi-static where time was used as a device to control the moving contact. In the final solution, a total of 560 time increments were used for the complete mandrel movement.

RESULTS

The first result was the residual stress distribution calculated from a conventional theoretical solution for 83 percent overstrain. This solution is shown in Figure 2 and represents the conventional picture of stress for this problem. In order to provide a good comparison, the 83 percent overstrain value was taken from the contour plots generated by this finite element solution. Note that the axial stress was assumed to be zero (plane-stress).

The first finite element results became available during the 15-hour solution time as the intermediate data were calculated. These show a rapid build-up of stresses ahead of the mandrel and the development of residuals behind the contact surface. These contour plots were reduced to a single typical contour plot of Mises' equivalent stress in Figure 3. This figure shows a large irregular 'bubble' of plastic tube material next to the contact surface.

The contact surface stresses are shown in Figure 4 as a function of axial position. The mandrel shape is shown along with the contact stress at two different mandrel positions: time increments 200 and 300. This allows the reader to relate the stress values to the position of the flat at the maximum mandrel diameter. The plot is consistent at each mandrel position but is rather jagged because the elements are rather large relative to the contact surface length. The entire contact surface length is only 5 elements long with the flat represented by a single mandrel element.

Figure 5 shows the residual stress versus radius data produced by this finite element solution. It corresponds to the stresses shown in Figure 2 for conventional equations. While the values at the inner diameter (ID) and OD seem to show reasonable agreement, the shape of the curves within the cylinder wall are rather different. Furthermore, the axial stress curve is not predicted by the conventional equations.

DISCUSSION

The most striking difference between this solution and the conventional hydraulic autofrettage solution is the very high interface pressure on the short contact surface. The same effect was predicted by this author in an earlier work on swage mandrels (7). This analysis method duplicates the mandrel analysis as a small part of the more general work. However, in this case the proper loading condition on the mandrel is also part of the solution.

This solution was difficult because the contact surface moves along the length of the tube producing residual stresses as a continuous process. The primary effects of this process exist only on a small portion of the tube at any one point in time. It is difficult to assume that this is equivalent to the hydraulic autofrettage process in which the entire tube is loaded at the same time. Unfortunately, the state-of-the-art in computation made this assumption necessary, if any engineering progress were to be made.

Any calculated stress distribution is open to doubt until it has been verified by experiment. In this case, the experiments have been difficult, expensive, and infrequent. The early work of Davidson (8) using the Sachs method and Clark (9) using X-ray diffraction both yielded data which are difficult to interpret. Both of these papers also used swage mandrels which were of a different design than those in current use. Current work in residual stress measurement yields encouraging results that will be published in a future report.

CONCLUSION

The use of the ABAQUS finite element code has been demonstrated for the full swage autofrettage problem. This opens the possibility of using this method of analysis for future problems. Furthermore, some of the results show residual stress effects which are not predicted by conventional analysis. These effects have been produced by modeling the process geometry, including the 'moving contact surface' effect.

REFERENCES

1. R.E. Weigle, "Elastic-Plastic Analysis of a Cylindrical Tube," WVT-RR-6007, Watervliet Arsenal, Watervliet, NY, March 1960.

2. R E. Weigle and M.J. Pascual, "Residual Stress in Circular Tubes Having a History of Pressure-Induced Plastic Deformation," WVT-RR-6014-R, Watervliet Arsenal, Watervliet, NY, December 1960.

3. T.E. Davidson, C.S. Barton, A.N. Reiner, and D.P. Kendall, "Overstrain of High Strength, Open End Cylinders Of Intermediate Diameter Ratio," Proceedings of the First International Congress on Experimental Mechanics, Pergamon Press, Oxford, 1963, pp. 335-352.

4. T.E. Davidson, C.S. Barton, A.N. Reiner, and D.P. Kendall, "A New Approach to the Autofrettage of High Strength Cylinders," Experimental Mechanics, February 1962, pp. 33-40.

5. ABAQUS User's Manual, Version 4.8, Hibbitt, Karlsson, and Sorensen, Inc., Providence, RI, 1989.

6. G.P. O'Hara, "Elastic Stress of Short Cylindrical Swage Mandrels," Proceedings of the Third Navy-NASTRAN Colloquium, March 1972.

7. H. Goodheim and G.P. O'Hara, "Finite Element Analysis of Several Swage Mandrel Designs," WVT-TR-74011, Benet Weapons Laboratory, Watervliet, NY, June 1974.

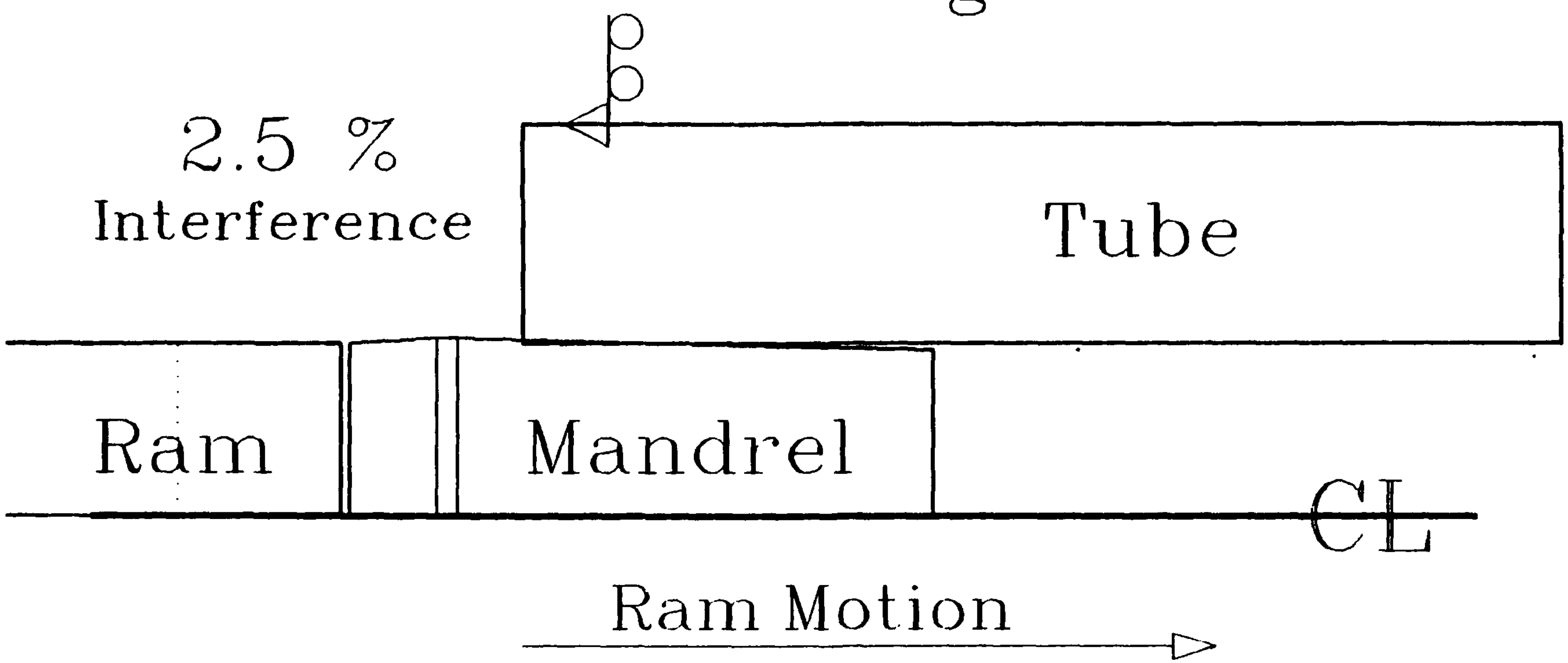
8. T.E. Davidson, D.P. Kendall, and A.N. Reiner, "Residual Stresses in Thick-Walled Cylinders Resulting From Mechanically Induced Overstrain," Experimental Mechanics, November 1963, pp. 253-262.

9. G. Clark, "Residual Stresses in Swage-Autofrettaged Thick-Walled Cylinders," MRL-R-847, Materials Research Laboratory, Department of Defence Support, Commonwealth of Australia, 1982.

105 mm Swage Process Geometry

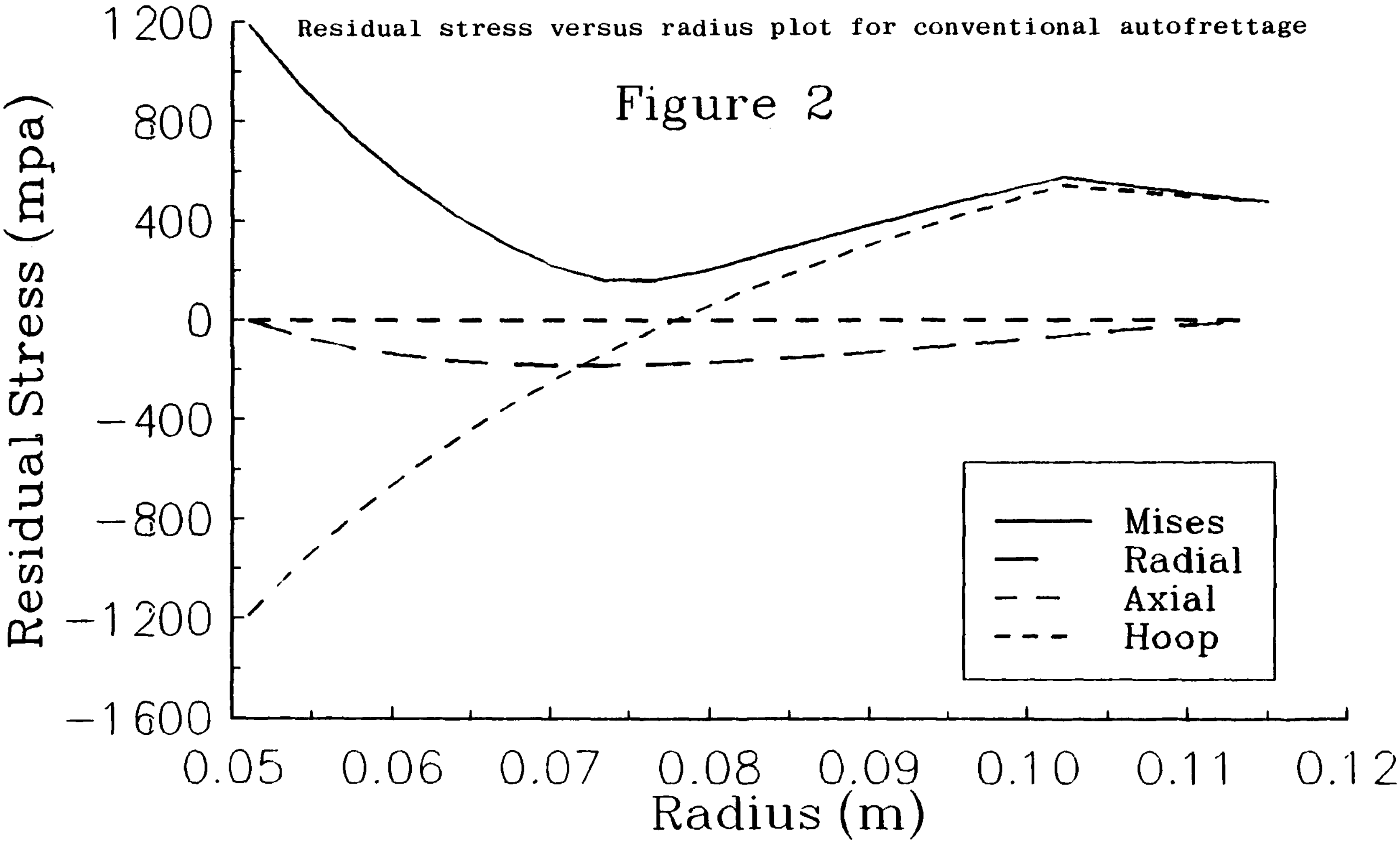
Longitudinal section of the swage process geometry

Figure 1



105 mm Autofrettage

80 % Overstrain



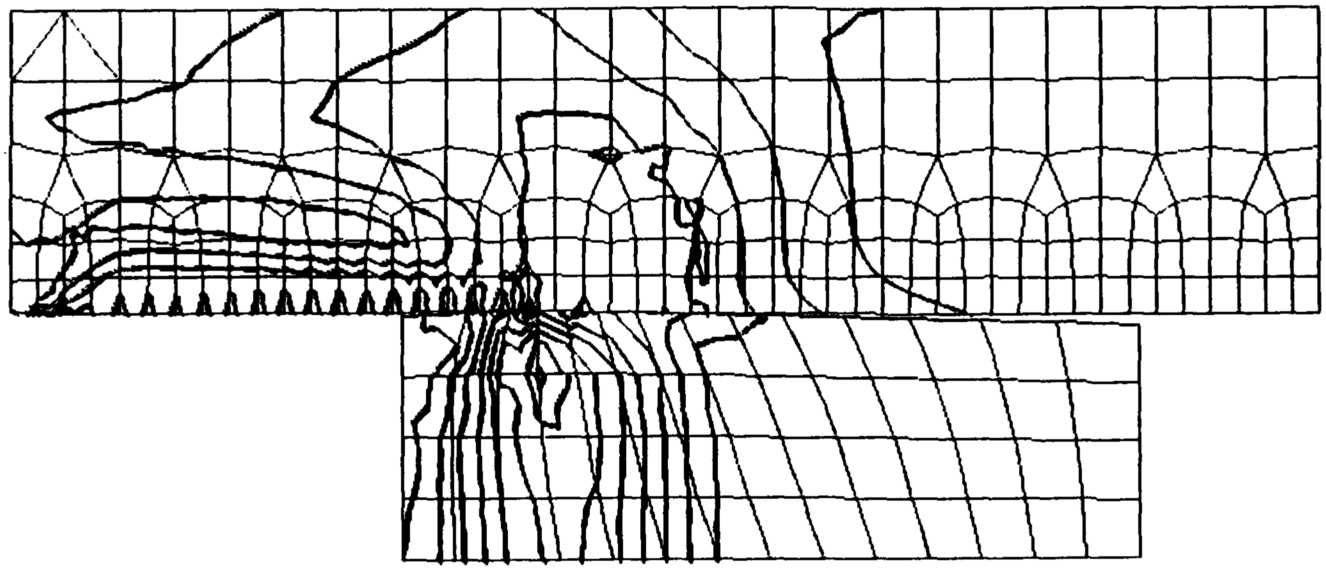
Residual stress versus radius plot for conventional autofrettage

Figure 2

105 mm Swage
Stress Contour

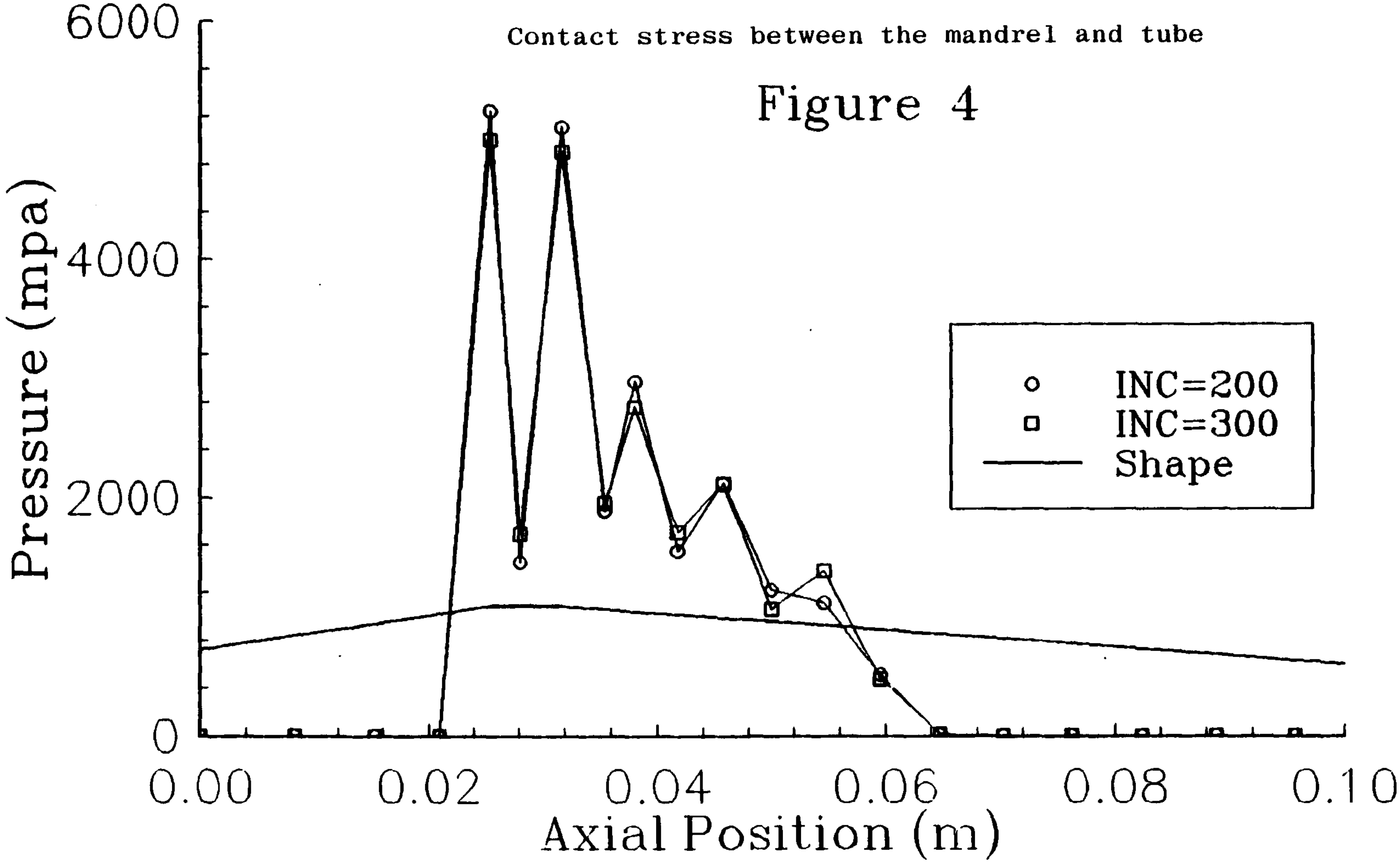
Mises' equivalent stress contours during the swage process

Figure 3



Mises Stress

105 mm Swage
Interface Stress



Contact stress between the mandrel and tube

Figure 4

105 mm Swage
As Swaged

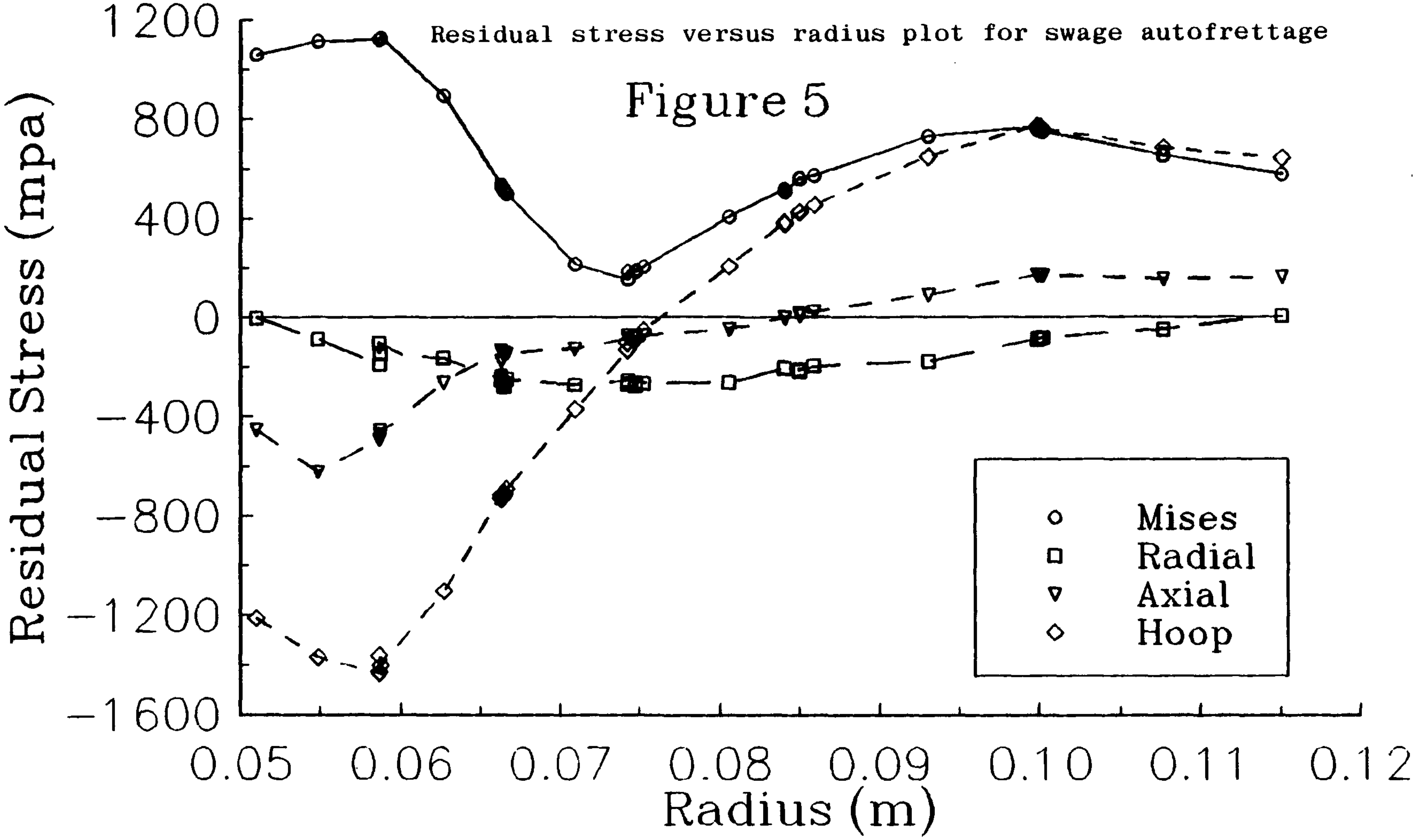


Figure 5

TECHNICAL REPORT INTERNAL DISTRIBUTION LIST

	NO. OF COPIES
CHIEF, DEVELOPMENT ENGINEERING DIVISION	
ATTN: SMCAR-CCB-DA	1
-DC	1
-DI	1
-DR	1
-DS (SYSTEMS)	1
CHIEF, ENGINEERING SUPPORT DIVISION	
ATTN: SMCAR-CCB-S	1
-SD	1
-SE	1
CHIEF, RESEARCH DIVISION	
ATTN: SMCAR-CCB-R	2
-RA	1
-RE	1
-RM	1
-RP	1
-RT	1
TECHNICAL LIBRARY	5
ATTN: SMCAR-CCB-TL	
TECHNICAL PUBLICATIONS & EDITING SECTION	3
ATTN: SMCAR-CCB-TL	
OPERATIONS DIRECTORATE	1
ATTN: SMCWV-ODP-P	
DIRECTOR, PROCUREMENT DIRECTORATE	1
ATTN: SMCWV-PP	
DIRECTOR, PRODUCT ASSURANCE DIRECTORATE	1
ATTN: SMCWV-QA	

NOTE: PLEASE NOTIFY DIRECTOR, BENET LABORATORIES, ATTN: SMCAR-CCB-TL, OF ANY ADDRESS CHANGES.

TECHNICAL REPORT EXTERNAL DISTRIBUTION LIST

	NO. OF COPIES
ASST SEC OF THE ARMY RESEARCH AND DEVELOPMENT ATTN: DEPT FOR SCI AND TECH THE PENTAGON WASHINGTON, D.C. 20310-0103	1
ADMINISTRATOR DEFENSE TECHNICAL INFO CENTER ATTN: DTIC-FDAC CAMERON STATION ALEXANDRIA, VA 22304-6145	12
COMMANDER US ARMY ARDEC ATTN: SMCAR-AEE	1
SMCAR-AES, BLDG. 321	1
SMCAR-AET-O, BLDG. 351N	1
SMCAR-CC	1
SMCAR-CCP-A	1
SMCAR-FSA	1
SMCAR-FSM-E	1
SMCAR-FSS-D, BLDG. 94	1
SMCAR-IMI-I (STINFO) BLDG. 59 PICATINNY ARSENAL, NJ 07806-5000	2
DIRECTOR US ARMY BALLISTIC RESEARCH LABORATORY ATTN: SLCBR-DD-T, BLDG. 305 ABERDEEN PROVING GROUND, MD 21005-5066	1
DIRECTOR US ARMY MATERIEL SYSTEMS ANALYSIS ACTV ATTN: AMXSY-MP ABERDEEN PROVING GROUND, MD 21005-5071	1
COMMANDER HQ, AMCCOM ATTN: AMSMC-IMP-L ROCK ISLAND, IL 61299-6000	1

	NO. OF COPIES
COMMANDER ROCK ISLAND ARSENAL ATTN: SMCRI-ENM ROCK ISLAND, IL 61299-5000	1
DIRECTOR US ARMY INDUSTRIAL BASE ENGR ACTV ATTN: AMXIB-P ROCK ISLAND, IL 61299-7260	1
COMMANDER US ARMY TANK-AUTMV R&D COMMAND ATTN: AMSTA-DDL (TECH LIB) WARREN, MI 48397-5000	1
COMMANDER US MILITARY ACADEMY ATTN: DEPARTMENT OF MECHANICS WEST POINT, NY 10996-1792	1
US ARMY MISSILE COMMAND REDSTONE SCIENTIFIC INFO CTR ATTN: DOCUMENTS SECT, BLDG. 4484 REDSTONE ARSENAL, AL 35898-5241	2
COMMANDER US ARMY FGN SCIENCE AND TECH CTR ATTN: DRXST-SD 220 7TH STREET, N.E. CHARLOTTESVILLE, VA 22901	1
COMMANDER US ARMY LABCOM MATERIALS TECHNOLOGY LAB ATTN: SLCMT-IML (TECH LIB) WATERTOWN, MA 02172-0001	2

NOTE: PLEASE NOTIFY COMMANDER, ARMAMENT RESEARCH, DEVELOPMENT, AND ENGINEERING CENTER, US ARMY AMCCOM, ATTN: BENET LABORATORIES, SMCAR-CCB-TL, WATERVLIET, NY 12189-4050, OF ANY ADDRESS CHANGES.

TECHNICAL REPORT EXTERNAL DISTRIBUTION LIST (CONT'D)

	NO. OF COPIES
COMMANDER US ARMY LABCOM, ISA ATTN: SLCIS-IM-TL 2800 POWDER MILL ROAD ADELPHI, MD 20783-1145	1
COMMANDER US ARMY RESEARCH OFFICE ATTN: CHIEF, IPO P.O. BOX 12211 RESEARCH TRIANGLE PARK, NC 27709-2211	1
DIRECTOR US NAVAL RESEARCH LAB ATTN: MATERIALS SCI & TECH DIVISION CODE 26-27 (DOC LIB) WASHINGTON, D.C. 20375	1 1
DIRECTOR US ARMY BALLISTIC RESEARCH LABORATORY ATTN: SLCBR-IB-M (DR. BRUCE BURNS) ABERDEEN PROVING GROUND, MD 21005-5066	1

	NO. OF COPIES
COMMANDER AIR FORCE ARMAMENT LABORATORY ATTN: AFATL/MN EGLIN AFB, FL 32542-5434	1
COMMANDER AIR FORCE ARMAMENT LABORATORY ATTN: AFATL/MNF EGLIN AFB, FL 32542-5434	1
MIAC/CINDAS PURDUE UNIVERSITY 2595 YEAGER ROAD WEST LAFAYETTE, IN 47905	1

NOTE: PLEASE NOTIFY COMMANDER, ARMAMENT RESEARCH, DEVELOPMENT, AND ENGINEERING CENTER, US ARMY AMCCOM, ATTN: BENET LABORATORIES, SMCAR-CCB-TL, WATERVLIET, NY 12189-4050, OF ANY ADDRESS CHANGES.